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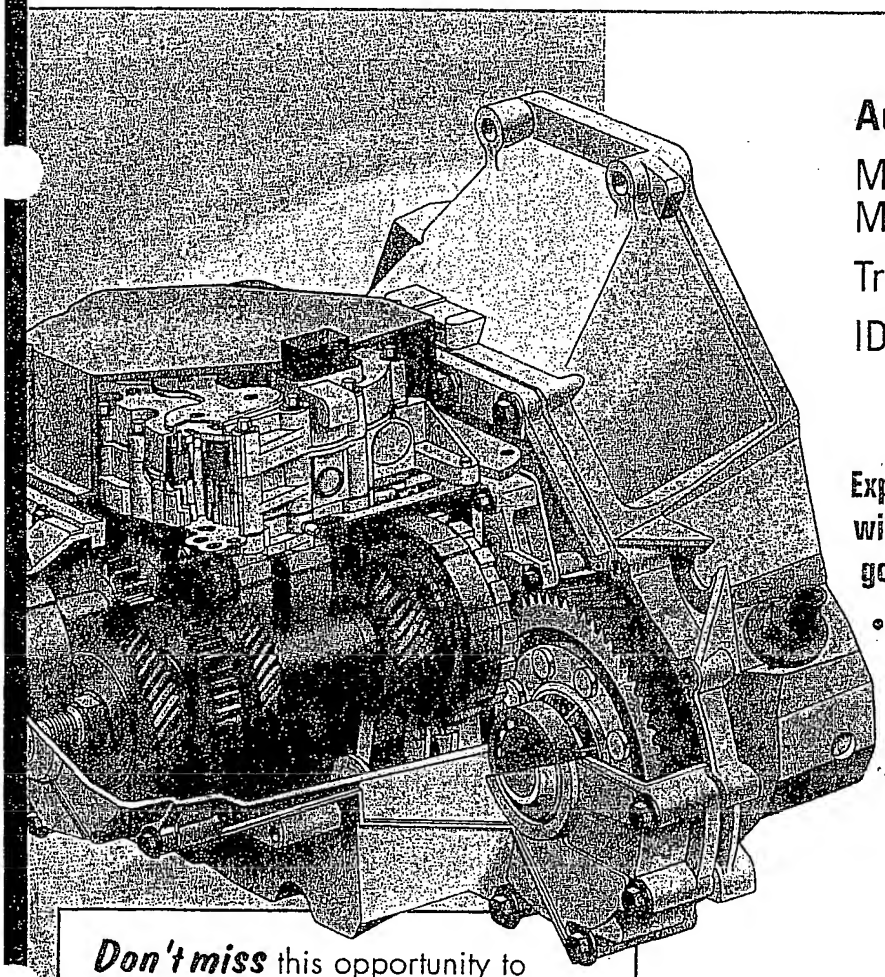

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Hybrid Hydraulic Powertrains: State of the Art and a Vision of the Future

Brad Bohlmann
Marketing Manager, Advanced Technology
Eaton Corporation

Hybrid hydraulic powertrains and powertrain sub-systems offer an alternative to hybrid electric solutions in a wide variety of applications. In particular, the high power density of hydraulics provides significant advantages in vocations that do numerous start/stop cycles during their daily operation. This paper provides an overview of the parallel hybrid hydraulic regenerative braking technology. Topics covered include pros and cons, applicability, performance characteristics of the technology. An overview of many of the possible embodiments of the hybrid hydraulic regenerative braking system is also presented.

♦♦♦♦♦♦♦

Brad Bohlmann is currently Marketing Manager for the Advanced Technology team in Eaton's Fluid Power Group. He received an MBA from the University of St. Thomas, an MS in Engineering (Mechanical) from the University of Michigan-Dearborn, and a BSME from the University of Minnesota. Prior to joining Eaton, he held several positions at Cummins Power Generation (Onan) including Senior Engineer, Manager of Fuel Systems & Regulatory, and Manager of Technical Services. He began his engineering career with Chrysler Motors in Highland Park, MI. At Chrysler, he worked as an engineer in the Advance Powerplant, Final Drive, and Lead Engine Engineering groups. He has been an SAE member since 1986.

EATON

Hybrid Hydraulic Powertrains: History, Current Status, and a Vision of the Future

Brad Bohlmann
Eaton Corporation
SAE TOPTEC Symposium on Emerging Transmission Technologies
August 13, 2003

What is a Hybrid Hydraulic System?

- Hybrid hydraulic systems provide some or all of the propulsion power for a vehicle.
- Hybrid hydraulic systems can provide significant improvements in fuel economy, tailpipe emissions, and vehicle operating costs.
- As with hybrid electric systems, both series and parallel hybrid hydraulic systems are possible.

Hydraulics: Key Equations

- Torque = displacement x pressure / 2π
- Power = pressure x flow / 1714

  = torque x speed / 63025
- Flow = displacement x speed / 231

Units:

- Torque: lb-in
- Displacement: in^3/revolution
- Pressure: psid
- Power: $hp_{hydraulic}$
- Flow: gallons/minute (gpm)
- Speed: revolutions/minute (rpm)

History of Hybrid Hydraulic Systems

- Mitsubishi Fuso
- Voac
- Parker
- Bosch
- GM
- Ford

Why Hydraulics?

- High power density
- High energy transfer rate
- Leverages proven technologies
- Packaging (size, flexibility)

Why Now?

- Significant improvements have been made recently in a number of areas including:
  - Leakage
  - Noise (NVH)
  - Efficiency
  - Electrohydraulic controls
- Market drivers including demand for improved operating costs and lower exhaust emissions.

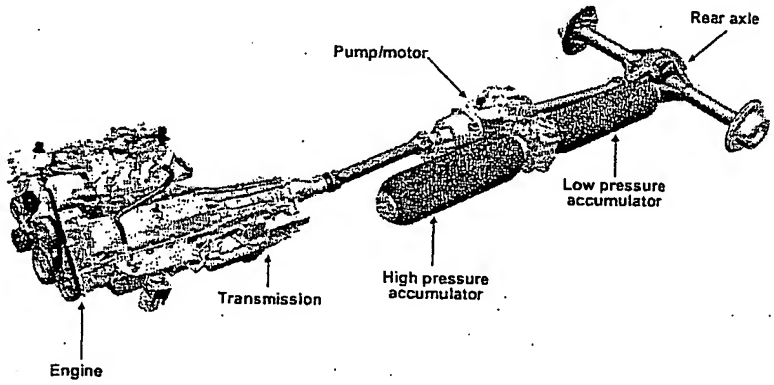
Hydraulic Regenerative Braking

- The high power density and high energy transfer rate of hydraulics make it feasible to develop regenerative braking systems that have payback periods that make them commercially attractive.
- In vehicles whose duty cycle includes frequent starts and stops, payback periods of 23 years are possible.

The Eaton HLA System

- The Eaton HLA system is a parallel hybrid hydraulic regenerative braking system.
- The HLA system recovers energy normally wasted as heat during braking. This recovered energy is used to supplement the engine's power during acceleration.
- The HLA system provides the greatest benefit when the vehicle's driving cycle involves stop and go driving.

Eaton HLA System: Typical Light & Medium Duty Installation



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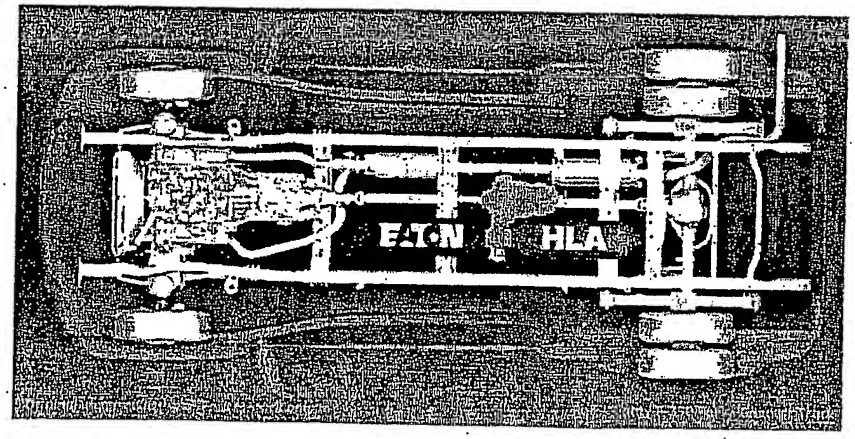
Eaton HLA System: Typical Light & Medium Duty Installation



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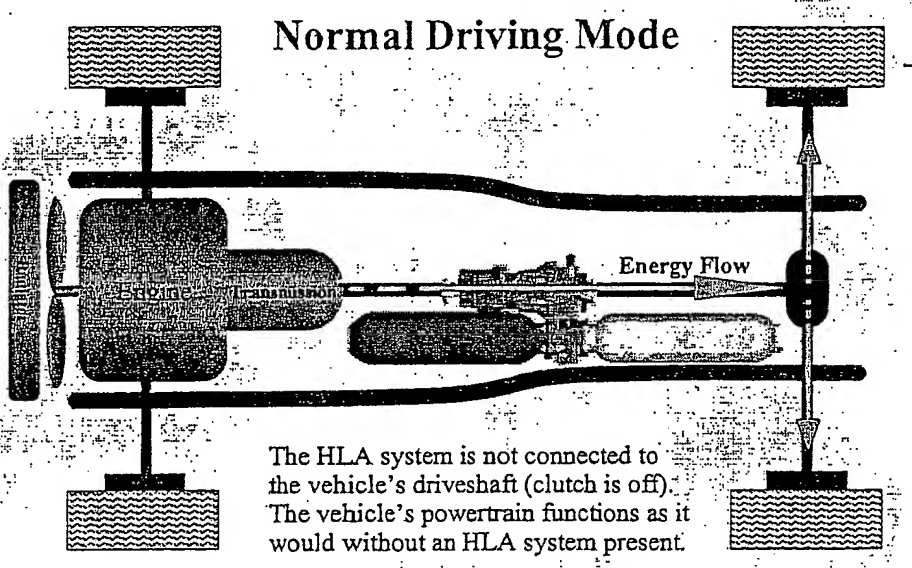
Normal Driving Mode



The HLA system is not connected to the vehicle's driveshaft (clutch is off). The vehicle's powertrain functions as it would without an HLA system present.

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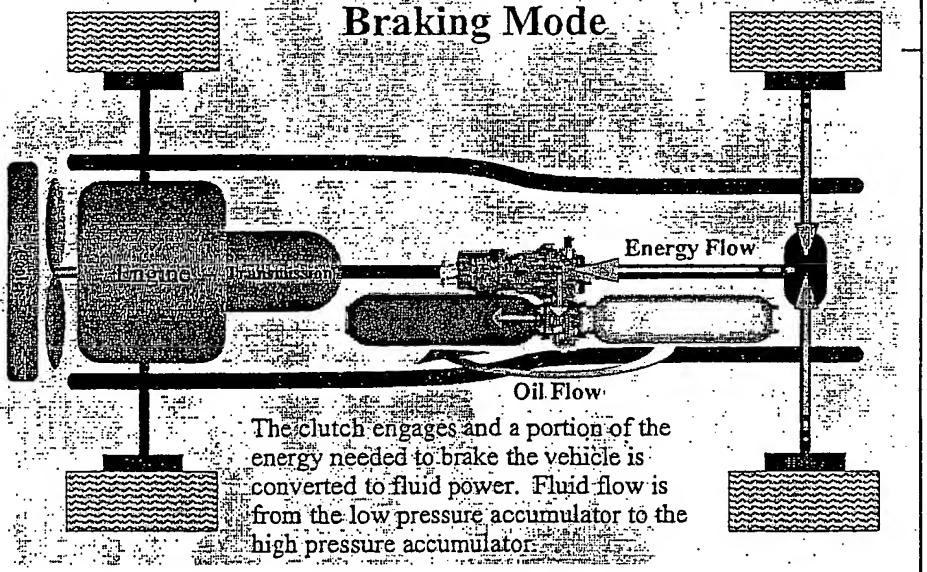
Braking Mode



The clutch engages and a portion of the energy needed to brake the vehicle is converted to fluid power. Fluid flow is from the low pressure accumulator to the high pressure accumulator.

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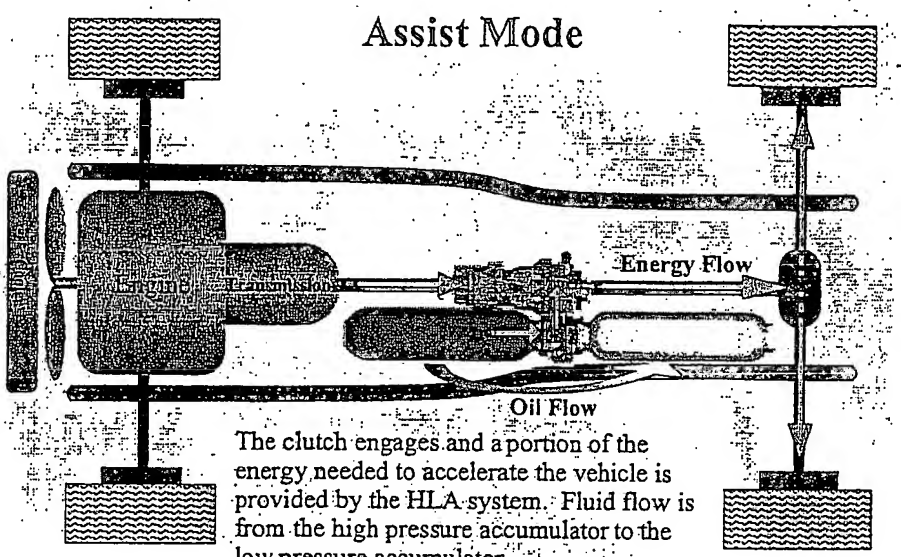
Assist Mode

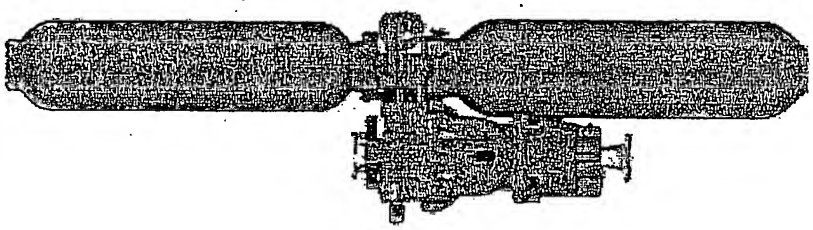


The clutch engages and a portion of the energy needed to accelerate the vehicle is provided by the HLA system. Fluid flow is from the high pressure accumulator to the low pressure accumulator.

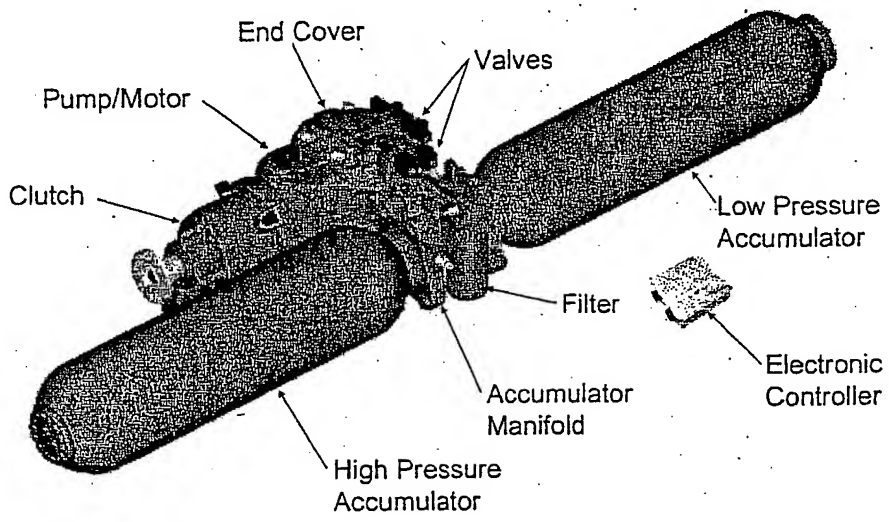
Eaton HLA System Specifications

Displacement:	9 in^3 (150 cc/rev)	15 in^3 (250 cc/rev)
Maximum Power:	275 hp (205 kW)	380 hp (285 kW)
Maximum Torque:	600 lb-ft (810 N-m)	1000 lb-ft (1350 N-m)
Energy Storage:	510 hp-s (380 kJ)	750 hp-s (560 kJ)

Systems have digital electronic control with vehicle CAN interface



HLA System Main Components



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HLA System Components

- Most of the components in the HLA system leverage the proven technologies found in Eaton's current hydraulics products.
- The accumulators are the main component on which the "state of the art" product on the market today was found to be wanting when applied to the HLA system.

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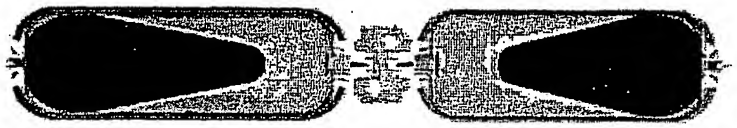
HLA System Components

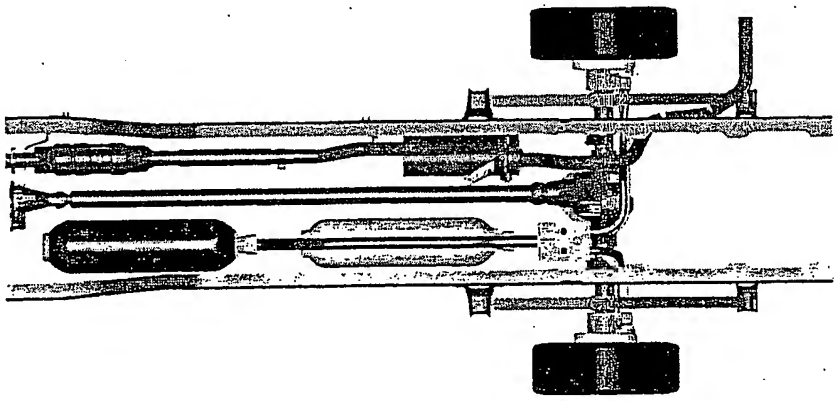


- The HLA system accumulators have the following characteristics:
  - Hydro-pneumatic: Nitrogen gas is used to store the energy
  - Composite carbon/epoxy shell
  - Thermoplastic liner
  - Very low permeation membranes

Hybrid Hydraulic Regenerative Braking System Packaging

- The packaging flexibility of hydraulics offers many possible embodiments of the Eaton HLA system. Several of the more likely are pictured on the following slides.

Wheel motors



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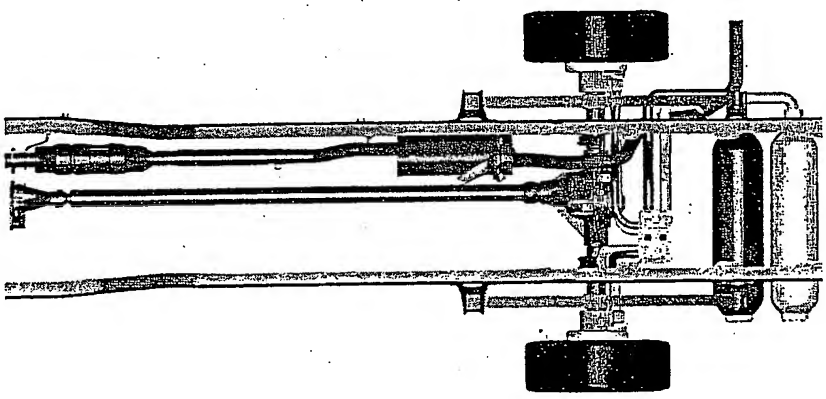
Wheel motors



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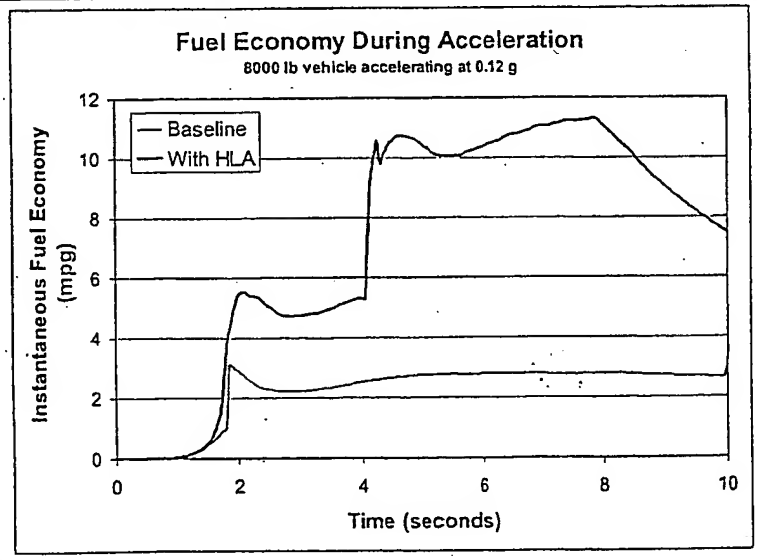
The HLA System Value Proposition

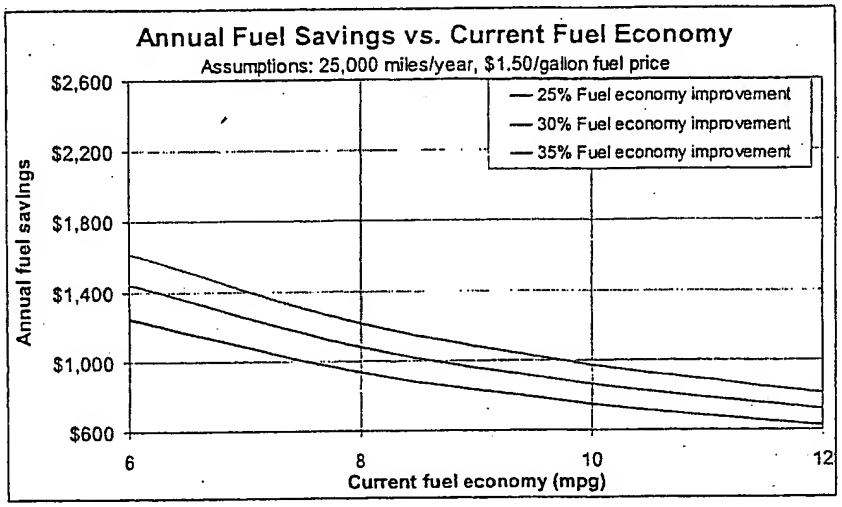
Quantifiable Benefits

- Fuel economy improvements
  - 25-35% on light-duty vehicles, higher on heavier vehicles
  - In many applications, the engine can be downsized with no loss of performance resulting in even higher FE improvements
- Brake maintenance savings
  - up to 70% longer brake life on an 8,500 lb GVW truck
- Productivity improvements
  - Faster acceleration / shorter cycle times
  - Integration with work circuits on vehicles with existing hydraulic infrastructure
- Potential hybrid tax credits could reduce payback period

The HLA System Value Proposition



The HLA System Value Proposition



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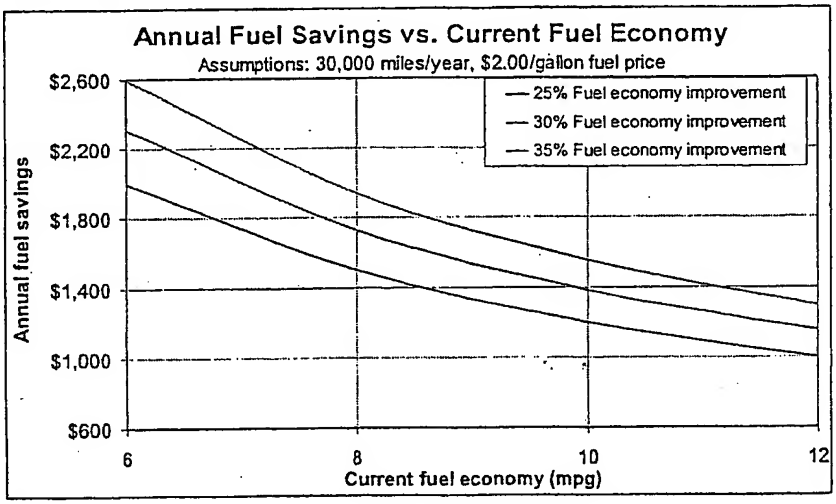
The HLA System Value Proposition



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The HLA System Value Proposition

More Intangible Benefits

- Lower exhaust emissions
- Reduced wear and tear on engine and transmission

Potential Hybrid Hydraulic Technology Roadmap